# Identifying and meeting new challenges in shallow-water acoustics

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## ABSTRACT

The past two decades have seen steady progress in understanding ocean acoustic effects, including some that are perhaps unique to the outer continental shelf. Progress has come from improved measurements, improved computational modelling, rapidly accumulating theoretical explanations, and the synthesis of these. The improved knowledge presents a new challenge, from an acoustics standpoint, to move beyond treating the ocean as containing slowly evolving but perhaps knowable synoptic features along with unknowable details at smaller scale, and to instead treat the small scales as predictable, to a degree. Another challenge regards how to incorporate the added information into systems. The over-arching challenge is determining how best to apply our new knowledge. The community is addressing the stated challenge of making higher-fidelity predictions of sound propagation conditions by moving towards jointly modelling recently investigated acoustically important small-scale ocean features and phenomenon, and their precise acoustic effects, using coupled computational models.

## INTRODUCTION

Many acoustic propagation effects of the outer continental shelf are now much better known to the research community than they were two decades ago. This progress has been enabled by field experiments with better environmental data, more detailed computational modelling, accumulating theoretical explanations, and sustained effort by dedicated researchers. The new understanding of how complex and time-dependent ocean conditions affect underwater sound has generated some new challenges. For instance, the episodic nature of packets of energetic internal waves gives an intermittency to some acoustic effects, and the anisotropic nature of those wave packets makes the acoustic effects anisotropic, setting up challenge number one: *Can we predict the time of arrival and direction of these waves?* This leads directly to another challenge: *Can we use these (hypothetical) wave predictions to make meaningful predictions of mean and fluctuating acoustic field properties*? Finally, because the strong intermittent effects may impact sonar systems and underwater communication systems, a third challenge arises: *Can information from the ocean wave or acoustic predictions, or both, be incorporated into the functionality and signal-handling protocols of real systems*? Success in pursuing each of these challenges is recognizably difficult, but would potentially allow more interactive use of underwater sound from the standpoint of tailoring systems and protocols to measured environmental conditions beyond what is done today.

Another set of challenges pertains to the zone just offshore, at continental slopes, which can be simple in form, or complicated by ridges and canyons. At these locations, the geological layering and sedimentation are likely to be difficult to measure and less well known than in flat locations. Acoustic inversion methods to obtain geoacoustic properties of the seabed, critical to know to make accurate predictions of bottom-interacting sound, may be particularly difficult to implement at slopes. The difficulties arise in the placement of seabed instrumentation, and in the geometrical assumptions often used to estimate the seabed properties, usually a layered assumption. Thus: *Can we apply our outer-shelf methods to slopes and canyons, or are their challenges (large depth, multiscale nature, three-dimensionality and nonlinear processes) too great?*

The four challenges listed above in italics have arisen from field studies of the last 15 years in areas of the outer shelf with strong vertical density gradients in the summer, where the action of the ocean tide at the shelf edge features leads to strong and variability internal tides, and where the interface of seasonally-varying shelf water and temporally stable deep ocean water can lead to temperature and salinity fronts. These challenges are unified in that they address the overarching concept of *understanding, predicting, and working around the strong variability encountered in this zone, or using it to advantage, including at the acoustic systems level*. This concept pertains other critical control factors for ocean acoustics, such as small-scale variability of seabed material, roughness, or subbotom structure, and anisotropy of bathymetric variations (i.e. sand wave or ripple fields). Thus, the discussion of how to apply the new knowledge goes beyond the specific outer shelf effects touched on here. In simple terms, each of the challenges has arisen from targeted successes, and an overarching challenge can be stated as *can we put all of these pieces together*?

## PROGRESS IN OUTER-SHELF ACOUSTICS

### Field program findings

The knowledge gained by deployments in the field has resulted in part by using ever-larger sets of better and cheaper sensors, for both sound and the environment, and using improved mooring technology that is more reliable and easier to use. Although environmental arrays have grown in size, they still cannot comprehensively sample the temporally evolving three-dimensional ocean volume for a typical low- to mid-frequency exercise (100 to 1500 Hz). Nonetheless, the improvements have allowed more complete sets of environmental measurements, and digital electronics advances have had great impact on acoustic systems. Contemporaneous ocean field and acoustic field measurements have delineated a number of first-order effects. Some of these are shown here.

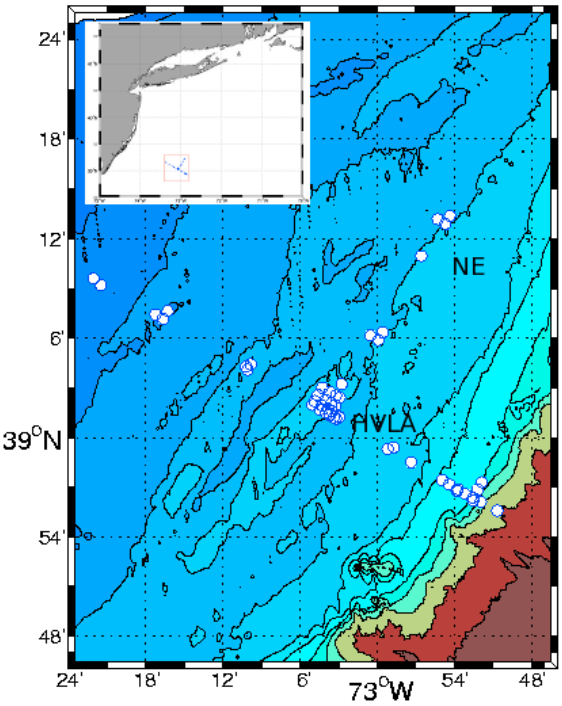

**Figure 1**. SW06 mooring locations (white circles) and bathymetry (contour interval 10 m at shallow depth in blue, larger interval at the steep slope of the lower right). The central cluster of 19 moorings (including the HVLA) where the two mooring lines intersect lies mostly in water slightly deeper than 80 meters. From Newhall et al., 2007.

Recently, the Shallow-Water 2006 (SW06) experiment South of New York sponsored by the US Office of Naval Research provided a number of detailed findings concerning propagation in episodic packets of anisotropic internal waves. Such waves create propagation effects that are distinct from fluctuations expected after propagation through a homogenous and isotropic random medium (i.e. homogenous and isotropic spectra of internal waves and eddies). Figure 1 shows the location and the arrangement of moored sensors that were “more comprehensive” than prior operations, to quote the terminology used above. The central cluster of 19 moorings contained an L-array (HVLA) with 32 hydrophones at 15-m spacing in a north/south line on the seabed, and a 16-channel vertical line array (VLA).

Figure 2 reproduces a figure from the *Internal Wave Atlas* (2004) that shows internal wave packets to be anisotropic, to move toward the coast, and to have directions and inter-wave spacings that are somewhat random. The properties of some of the waves in this area have been tabulated (Lynch et al., 2010). Figure 3 shows some first-order effects on the horizontal coherence length of sound propagated from a stationary source at the “NE” mooring triad (Figure 1) to the 19.6-km distant HVLA receiver in the presence of passing packets of high-amplitude and short-wavelength internal wave with crests parallel to the acoustic propagation path (as depicted in Figure 2 at latitudes near 39°30′ N). The coherence length is the scale where the mean product of spatially-lagged complex acoustic field values falls to exp(-1) times the zero-lag value; it is a strong indicator of the effectiveness of multiple-element array coherent signal processing in the discrimination of signal from noise. The horizontal refraction of sound by the long-crested internal waves has a strong effect on the spatial structure of the sound field and thus on the coherence length. Sound was also transmitted from the northwest end of the mooring line to the HVLA; these signals showed a short but steady coherence length of 12 wavelengths. The explanation for the steadiness is that sound crossed the internal waves, some of which were always present in the 32-km path, and the short-scale sound-speed gradients within the waves in the direction of the path made the waves act as multiple discrete scatterers via a mode coupling process (Zhou et al., 1991). The azimuthal dependence of shallow-water internal wave effects on sound has been recognized for some time (Badiey et al., 2002), with recent research providing an appreciation of the multitude of possible effects.

The northern South China Sea was the site of another recent experiment (2007). Sound pulses with 400-Hz centre frequency were propagated from a moored source to VLAs at 3-km and 6-km range on a line roughly parallel with crests of internal waves. Figure 4 shows 3D parabolic equation (PE) model results for sound refracted and ducted by simulated curved internal waves designed to fit observations by sensors at the VLAs and the source. The moving waves have a clear effect on the modelled sound field, and the predicted sound fields fit the observations well (Duda et al., 2011). 3D modelling of this type is discussed a few paragraphs below.

Many other acoustic effects have been tabulated in SW06 and other experiments, most of which are related either to horizontal refraction, as illustrated here, which is usually treated as refraction of identifiable acoustic normal modes trapped in the surface-to-bottom waveguide and not exchanging energy, or coupled normal mode propagation, which occurs when sound passes through waves or fronts which have strong sound-speed gradients in the direction of sound propagation, and the energy moves between modes. Thus, we have a relatively good (and improving) understanding of internal wave-induced sound propagation effects on the outer shelf. This leads directly to the question of what to do with this knowledge, because predicting waves and their acoustic effects would be a technical challenge.

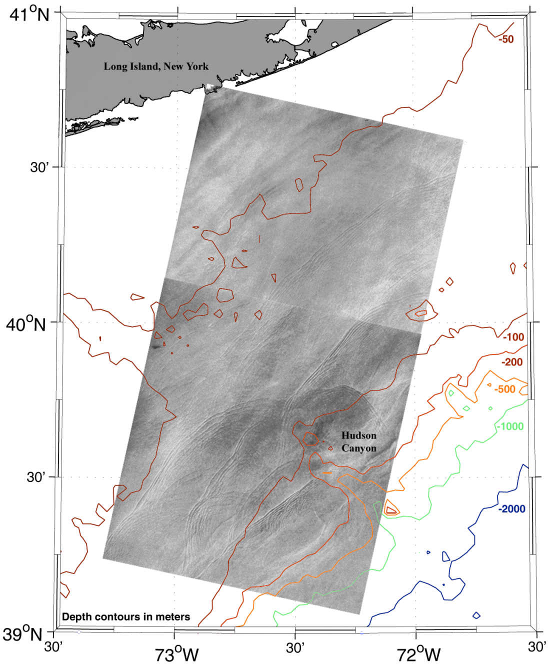

**Figure 2**. A satellite synthetic aperture radar image showing internal waves moving shoreward slightly to the north of the SW06 area. The light stripes are rough zones of surface current convergence, the dark are surface current divergence. From Jackson, 2004.

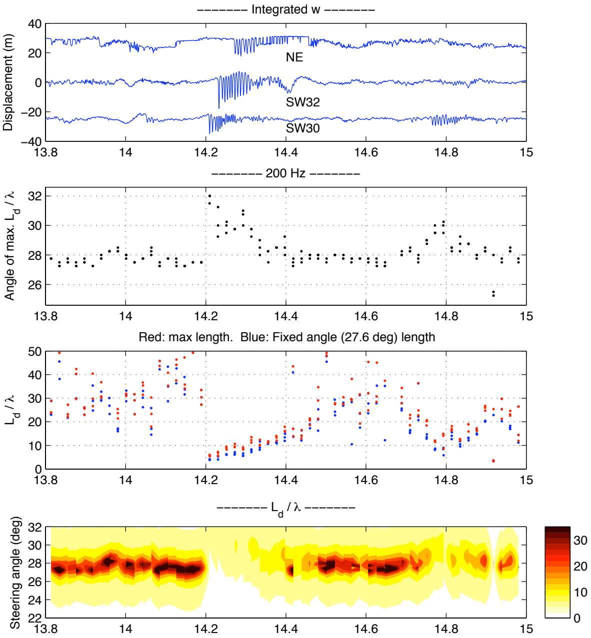

**Figure 3**. Horizontal coherence length of 200-Hz sound transmitted 19.6 km for a 1.2-day time period in SW06 (Aug 13-14). At the bottom are horizontal coherence length $L_d$ values, in wavelengths, as a function of time and horizontal array beam steering angle. Above that the maximum $L_d$ for each time is plotted. Above that, the angle of the maximum $L_d$ is plotted. At the top, time series of thermocline displacement near the source (NE), receiver (SW30) and midway (SW32) are plotted, showing an internal wave packet passing at the time of low signal coherence. From Duda et al., 2012.

## Modelling advances

Before moving on to the issue of wave predictions and acoustic predictions, recent advances in acoustic propagation modelling and ocean dynamical modelling capabilities are presented. Three-dimensional acoustic simulations in discretized volumes containing realistic ocean features has uncovered or confirmed the physical mechanisms of a number of acoustic effects such as those shown in the previous section.

Three-dimensional acoustic propagation models are now more commonly used than ever. The FOR3D 3D PE code (Lee and Schultz, 1995) has been superseded by some new split-step Fourier transform codes that allow better resolution and fidelity over larger areas and handle horizontal refraction differently (Lin et al., 2013a). The results shown in Figure 4 were generated using the Cartesian coordinate code. The Fourier PE methods are attractive because they intuitively separate the propagation into "free-space" propagation through a uniform medium, which is handled in the wavenumber domain, and phase adjustments controlled by refractive index structures, which are handled in the spatial domain, each process being done once each step as the monochromatic solution is generated in marching fashion from the source. The codes solve for pressure over the square-root of density, which has a discontinuity at the seafloor, so the density term must be smoothed vertically at the seafloor with a smoothing scale something like the acoustic wavelength. This is fine for frequencies above about 90 Hz, giving essentially the same results as for the discontinuous density situation. However, something else must be done at low frequency. For this situation, we have a 3D Padé rational approximation code that is implemented using Galerkin discretization (as with the commonly used 2D PE code RAM) that can handle the discontinuities (Lin et al., 2012).

Computational ocean dynamical models have been accurate and stable for many decades, for the scales of motion that they resolve, and for the specified initial and boundary conditions. The major challenges that have been addressed over the recent years concern resolution of small scales over large areas, open boundary condition specification, surface forcing specification, and initialization. Years ago these models were operated by specialists, but recent reductions in the cost of memory and processor power now make parallel computations over large domains with fine resolution within the reach of a large community, accelerating the pace of innovation. Among the recent advances are refinements of data assimilation procedures. Data assimilation enables sensor information to steer the ocean models towards reality; there are many implementation methods. One recent paper lists a few of the methods and implements one (Xu et al., 2013). Two-way nesting of model domains with tight grids within domains of coarse grid allows dynamically consistent horizontal grid refinement, allowing resolution of small features in areas of interest at reduced computational expense (Haley and Lermusiaux, 2010). Figure 5 shows a snapshot of temperature at 50-m depth in the western Pacific from a data-driven (data-assimilating) ocean model created for the 2008 QPE Pilot study (Lermusiaux et al., 2010).

## Theoretical frameworks

Theories of evolving complexity have explained both the observed and modelled effects. Coupled-mode theories for purely radial propagation have explained many of the effects of sound crossing fronts or internal wave crests, even above sloping seafloors (Chiu, et al., 2013). In this scenario, horizontal gradients of water or seabed properties in the direction of sound propagation cause energy to move between normal

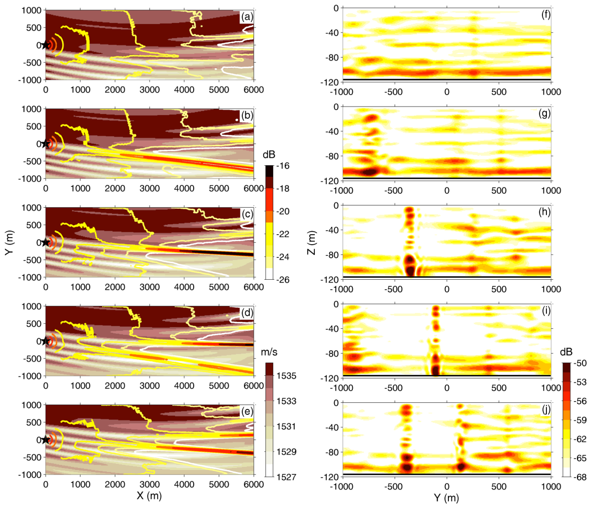

**Figure 4**. Focussing of 400-Hz sound trapped in internal-wave ducts and then escaping from the ducts is shown, computed with a 3D PE model. (Left) These are plan views of four time snapshots for a moving wave. The sound source is at [X,Y]=[0,0]. The colors show contours of depth-averaged sound (pressure squared). The shading shows internal-wave anomalies of sound speed at mid depth; light shades show ducts (waves of elevation, with slow modal phase speeds). (Right) The sound level is shown for the vertical planes at the right-hand edges (X=6000 m) of the left-side plots. From Duda, et al., 2011.

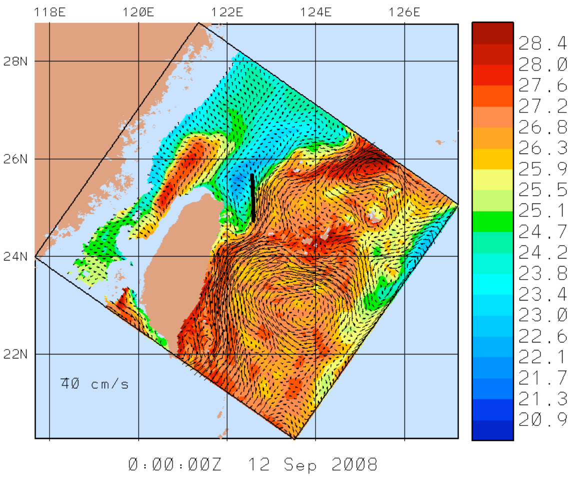

**Figure 5**. Temperature and current (arrows) at 50-m depth are plotted for the QPE pilot study model domain. The image is from http://mseas.mit.edu/Sea_exercises/QPE/.

modes. The fluctuating modal composition of the sound field causes fluctuating interference patterns, and also cause fluctuating energy levels because each of the normal modes interacts with the seabed in a unique way, with some modes penetrating more and being attenuated more.

Another theoretical construct is so-called vertical modes and horizontal rays (Weinberg and Burridge, 1974). In this scenario, normal modes do not exchange energy (are adiabatic), but refraction of modal energy in the horizontal is allowed, and is treated with ray theory. A higher level of complexity is to give the adiabatic normal modes a full-wave treatment, such as with a parabolic wave equation (Heaney et al., 2012).

Difficulties arise when mode coupling and mode refraction occur together, and neither of these otherwise powerful methods suffices. We call this "fully 3D" acoustics. For this, we now use computational methods such as the 3D parabolic equation and 3D coupled normal-modes. Various common ocean features that exhibit this behaviour are long-and short-wavelength internal waves (straight or curved), surface swell, sloping bathymetry, and fronts. Using the latest methods, Shmelev (2011) has documented situations where coupling and refraction are inseparable.

A theoretically interesting topic is the structure of normal modes in three dimensions. Here, the energy in vertical modes is divided into identifiable horizontal modes at locations where trapping features such as paired internal waves or fronts cause create laterally variable conditions (Finette and Oba, 2003, Lin et al., 2013b). What results is a double-indexed set of normal modes, with, for example, vertical mode number one supporting modes one-one, one-two, etc. The use of this concept helps us understand the often surprising and rich acoustic field patterns that arise in computations.

Theories also exist to describe propagation fluctuations within shelf environments filled with homogenous internal waves (e.g. Creamer, 1996, Ratilal and Makris, 2005, Rouseff and Tang, 2006, Colosi et al., 2012). These are very comprehensive for the given situation, but the variability shown in Figure 3 is not covered by these theories because they don't include anisotropic internal waves, do not yield predictions for azimuthal variations and deterministic variations (such as tidal) in statistics such as correlation length. Instead, they provide statistical quantities for stationary processes.

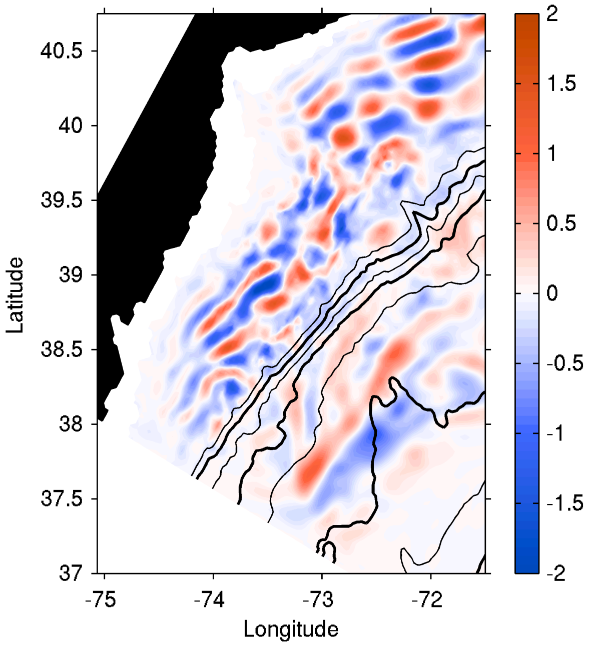

**Figure 6**. Semidiurnal bandpass-filtered temperature anomaly (ºC) at 30 m depth in a tidally and surface forced data-assimilative model of the Mid-Atlantic Bight area made by the MSEAS group at MIT. A 4-degree temperature change equates to about a 13 m/s sound speed anomaly, almost one percent. The lines show bathymetry, 500-m contour interval.

Lastly, for this section, progress has recently been made on evaluating the effects of uncertainty. Two of many examples are mentioned here. One recent study analyses the relative importance of tidal forcing, seabed parameters, source depth and background stratification on the spatial structure and size of intensity variance using polynomial chaos methods and 2D acoustics (Gerdes and Finette, 2012). Another recent paper uses dynamical models to assess uncertainty in the environment and acoustic propagation northeast of Taiwan using 2D acoustics in many radial planes (s-called N by 2D) (Lermusiaux et al., 2010).

## Building on this progress

Underwater sound propagation in complicated 3D time-dependent environments filled with submesoscale flow structures can be summarized in a few bullets:

- Internal waves, fronts, and other submesoscale features can heavily influence sound transmission loss (TL) and array directivity index (DI, akin to array gain) in shallow coastal seas.
- Some of the most important effects are linked to feature anisotropy. The acoustic signatures are also anisotropic.
- Many of the effects are transient and intermittent, because the features are so. (For example, packets of steep nonlinear internal waves.)

Prediction of the effect's appearance at a specific location, duration, and so on, may be valuable. However, although dynamical models have improved, deterministic or statistical prediction of feature alignment and location remains a challenge. In addition, many physics questions remain to be explored. Modelling short nonlinear internal waves (Figs. 2-4) whose vertical acceleration is non-negligible (having nonhydrostatic pressure) over large areas is computationally barely possible. Nonetheless, we present an approach to this in the next section. As an alternative to deterministic wave (and acoustic effect) prediction, mapping regime types over the globe, or conversely, identifying key feature types in given areas, may be a valuable secondary approach.

The overall challenge is: *Can we put all of these pieces together into something useful?*

## THE WAVE PREDICTION CHALLENGE

### Nonhydrostatic nonlinear internal wave formation

The short-wavelength nonlinear internal waves and wave packets that show the strong and intermittent acoustic effects (Figures 2-4) are by now familiar to most ocean scientists. These waves can be weakly or strongly nonlinear, and display nonhydrostatic pressure, a rare feature among phenomena of their scale. They can arise directly from flow of stratified fluid over uneven bathymetry, or indirectly from flow over bathymetry by arising from long-wavelength internal waves. (See Apel et al., (2007) for a review). Oscillatory tidal flow is the most common forcing flow for them in nature, and is responsible for most if not all of the short nonlinear waves seen in recent acoustic experiments. The generation of the long-wavelength waves (internal tide) at slopes is fairly well known after decades of study (Vlasenko et al., 2005), as is the steepening process (Helfrich and Grimshaw, 2008, Li and Farmer, 2011). However, because the theories are approximate and do not include small-scale effects such as boundary layer turbulence and internal dissipation, the precise behaviour in nature remains a topic of study.

### Nested internal wave modelling

Despite the knowledge gaps, enough is known about the dynamics of internal tide generation and short-wave formation that there may be value in trying to predict wave fields with numerical ocean models. The models can either provide forecasts of deterministic wave positions and properties, or of wave statistics. We have a project with a component to investigate the quality of such comprehensive modelling, including for acoustic predictions, called Integrated Ocean Dynamics and Acoustics (IODA). There are many principal investigators, a requirement because of the breadth of the scales and of the methods involved.

Because the data-driven 3D ocean dynamical models described in the “Progress” section use the hydrostatic pressure approximation, they cannot handle the short internal waves. (Including non-hydrostatic pressure and resolving short waves in the models makes them hundreds of times slower.) The models do include nonlinear dynamics, so the long waves can steepen if they have sufficiently large amplitude. This process in shown in Figure 7, which models the transition of a sine-wave internal tide hypothesized to form at Ilan Ridge moving northward across the southern portion of the Okinawa Trough. This figure shows the output of a model that includes nonhydrostatic effects. A hydrostatic model would properly reproduce the initial stages of wave steepening, but after that the wave shape would be improperly modelled. (The short waves would not appear, and the steepened long-wave profile would not be a natural shape.)

A composite internal wave model composed of a few different types of models nested in as rigorous fashion as possible is one approach to internal wave prediction. We are undertaking this right now. The method is to use data-driven hydrostatic regional models (themselves nested, Figure 8) to make predictions of mode-one internal tides moving onto the shelf (as illustrated in Figure 6). Ray-tracing methods, or full-wave methods, can be used to predict internal tide propagation onto the shelf, or it may be possible to extract these waves from the model. Two-dimensional non-hydrostatic wave evolution models (Apel et al., 2007, Holloway et al., 1999) are then used to generate the short internal waves that are of interest along the resultant shore-directed internal tide (long wave) trajectories (the short waves developing as in Fig. 7, although more rapidly in shallow water). An important step, which is now a matter of research, is to determine the internal tide propagation. The background “random medium” through which these waves propagate must be extracted from the model via filtering or possibly a more sophisticated method of switching off the tides (P. Lermusiaux, S. Kelly and P. Haley, personal communication). Simply running the model without the tides may not give the proper background state because tidal mixing and rectified tidal flow effects may influence shallow water dynamics. An interesting complicating factor is that internal-wave modes in water with a 2D sheared background current have anisotropic wave speed. This makes ray tracing more sensitive to initial conditions; our initial studies suggest that this may enhance internal tide wave crest focussing and thus short wave formation.

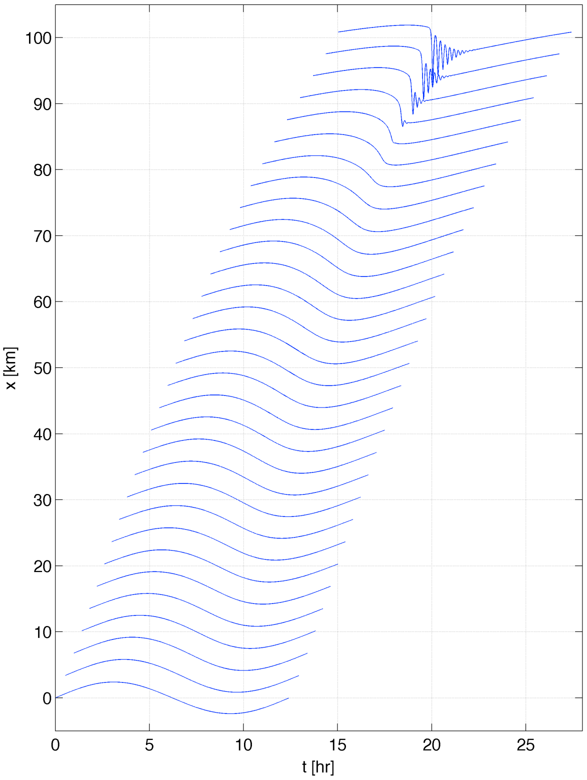

**Figure 7**. Time series of wave profiles from a nonlinear internal wave evolution model (Holloway et al., 1999). The model is initiated with a 24-m amplitude sine wave with 12.42 hr period (M2 tide). The model is set up to study a wave propagating south to north from Ilan Ridge to the shelf northeast of Taiwan along the black track in Figure 5. The wave steepens after traveling about 80 km, them transforms into a packet of short waves. The speed of the wave at the later stage is evident, 10 km in ~2 hours, about 1.4 m/s.

## THE ACOUSTIC PREDICTION CHALLENGE

Making 3D acoustic propagation predictions in areas where internal waves are predicted along tracks presents another set of difficulties to be overcome. Crossing rays (multipath) indicate that a full-wave approach would be needed. Disregarding this for the time being, the remaining task would be

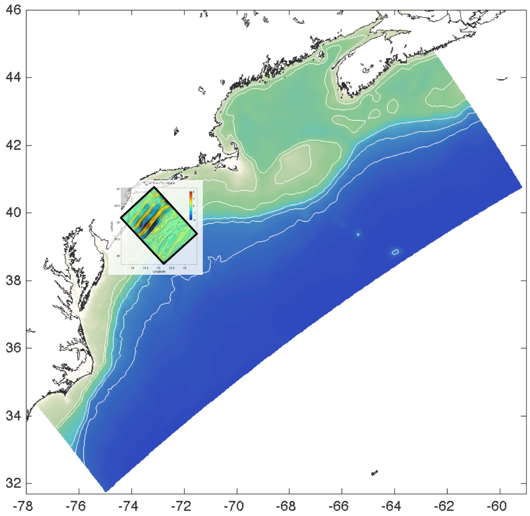

**Figure 8**. Bathymetry of the domain of the proposed enlargement of the Rutgers Univ. data-driven ESPreSSO model. Also shown are internal waves in a nested grid. Tighter-grid nested domains can have horizontal grid refinement of a factor of three, enabling localized internal-tide modelling.

to generate sound-speed structure within a volume. The fact that the short internal waves vary along tracks means that the short-wave modelling must be sufficiently dense. This is something we are working on now. Figure 9 shows a trial run of a few internal tide rays traced through a de-internal-tided MSEAS MIT ocean model field (Lermusiaux et al., http://mseas.mit.edu/Research/SW06/MSEAS_reanalysis/). Figure 10 shows a plan-view of a 2D (lat, long) interpolation of mode-one displacements generated along the rays using the cubic-order nonlinear rotation-modified extended Korteweg-DeVries wave evolution model (Holloway et al., 1999) and a simple sinusoidal initial condition. Note that the spatially incremented time-series solutions (see Figure 7) can been converted into spatial patterns along rays. Along-crest variations can be seen in the modelled short waves. To get the volumetric sound speed field, these amplitudes would need to be multiplied by the internal-wave mode shape at each point to yield displacement, and then the sound speeds at each point would be deduced by remapping the sound-speed profiles at each point to the displaced positions.

There are a few remaining issues to be tackled before passing 3D sound-speed fields like this to 3D acoustic models. The initial conditions for the internal tides should be taken from the larger-scale data-driven model (or from a strategically placed mooring). The effects of currents on the internal tide rays must be taken into account; a reasonable approach to this is to use the Taylor-Goldstein internal-wave mode equation (Thorpe, 2005) generalized to handle 2D currents. Finally, it must be verified that the data-driven model is formulated to have sufficient spatial resolution for proper internal tide generation (this is a research topic; Robertson, 2006), and has proper boundary conditions.

The 3D acoustic models that can take in such detailed volumetric ocean predictions are quite powerful and accurate at this time (Lin and Duda 2012, Ballard 2012, Lin et al., 2012, Lin et al., 2013, Sturm and Korakas, 2013), although necessarily more time consuming than 2D modelling. One topic that remains to be investigated is the degree of interpolation of the 3D ocean fields required to give an adequate converged acoustic solution. For the Fourier transform methods, (Lin et al, 2013) the needed grid size is of order one acoustic wavelength. However, the sound-speed field is generally only interpolated on to a grid with a spacing many times this. One can speculate that analysis of the Fresnel scale length for the modelled source-receiver geometry and the frequency would quantify the requirements for accurate simulation.

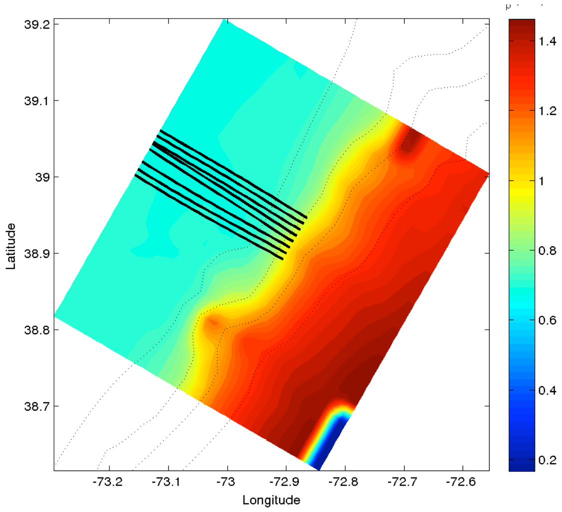

**Figure 9**. Seven mode-one internal-tide model rays originating along a line at the Mid-Atlantic shelf edge are shown. The internal-tide phase speed stabilizes near 0.8 m/s on the shelf This is a simplified simulation that ignores the effect of the background currents.

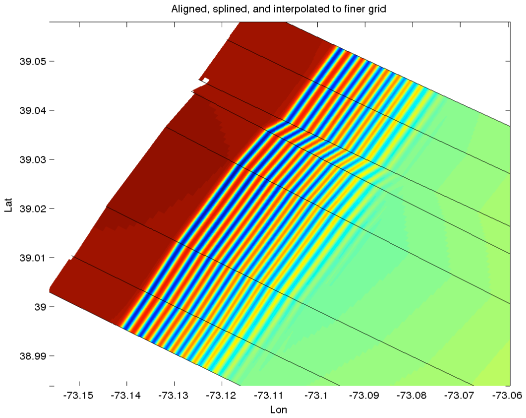

**Figure 10**. Mode-one internal wave amplitudes produced along each ray, which show ray-dependency of the wave packet. A smoothing and interpolation scheme is used to form the 2D field.

## THE SYSTEM INTEGRATION CHALLENGE

The possibility of making use at a system level of predictions of internal wave locations and directions, and of predictions of rapidly varying propagation effects is perhaps the strongest challenge. This can be viewed as system integration of environmental information. However, there is a strong counter desire to engineer systems that work under all conditions, perhaps not optimized for any particular situation, the opposite approach. It remains to be seen how quickly (or whether) optimization of signal frequencies, array-processing methods such as adaptive sub-aperture processing, detection schemes, or tracking schemes, will be adopted by the community.

## THE SLOPE-ZONE CHALLENGE

The final listed challenge regards the shelf edge, particularly areas with two-dimensionally varying gradient directions, such as canyon zones. Here, the low-angle water-column medium refractive effects occur within a propagation regime controlled largely by the high-angle reflective effects of the ocean floor. There is a stepping up of uncertainty in the acoustics, explained (for the case of no acoustic mode coupling from sharp water-column gradients) in this way: In the nearly flat-bottom situation, three-dimensional acoustic effects complicate propagation beyond a nearly cylindrical-spreading normal-mode background situation; whereas with a ridge or canyon, or even for sound obliquely incident on a simple 2D slope, the background situation is difficult to know because of seafloor-shape and seafloor-reflectivity uncertainty.

Regarding the additional effects of water-column structures, the topographic interaction of low-frequency flow patterns, mixing effects, and complex internal-tide generation and radiation, give these areas richly three-dimensional density and flow fields. Accurate modelling of the low-frequency flows requires a domain that is large enough to model the entire shelf area, such with the outer domain of Figure 8. However, fine nested grids are a necessity for the internal tides. Stepping back for a moment from the prospect of meaningful predictive modelling of time-dependent canyon conditions, to a simpler mean-state prediction, comparisons of 3D model sound fields with observations are only just beginning, with one recent paper showing imperfect agreement (Chiu et al., 2011). Considering our partial ignorance of the bathymetry, the seabed properties, and the three-dimensional sound-speed structure in the water (which determines where the sound reflected from the seafloor goes much more than for a flatter seafloor, because of the high degree of slope uncertainty and high slope gradients), is it not surprising that mean conditions in complex sloped areas are difficult to predict. This dual difficulty of mean and fluctuation prediction may not exist in flatter areas, where the mean state may be more predictable than the fluctuations, but this is speculation at this point.

## SUMMARY

Some recent progress in ocean physics studies, ocean dynamical modelling, and ocean acoustics fluctuation observation, modelling, and theory has been presented. Successful application of the new tools and new knowledge to move in a forward direction depends more than ever on researching acoustically relevant aspects of ocean physics, such as speed, direction, and location of internal wave packets, which may be of lesser interest to other ocean scientists. (They may be more interested in the integrated effect of internal waves on upward nutrient flux, for example, than on the features of specific waves.) Such studies may yield crucial information for predictive modelling of internal waves, on an as-required basis in limited areas, for the purpose of feeding information to 3D acoustic models, as has been outlined here.

## ACKNOWLEDGMENTS

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